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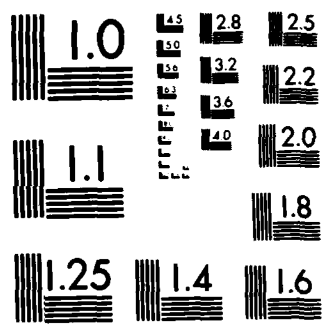

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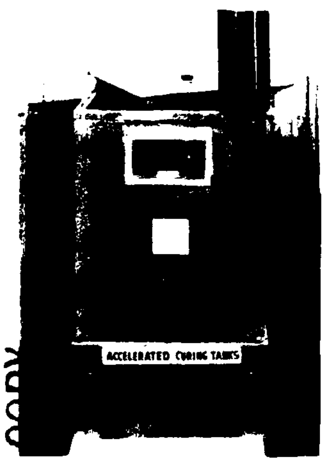

STRUCTURES LABORATORY

MISCELLANEOUS PAPER SL-84-13

COMPRESSIVE STRENGTH-MATURITY RELATIONSHIPS OF MORTAR CONTAINING FLY ASH

by

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October 1984

Final Report

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under CWIS Work Unit 31138

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Miscellaneous Paper SL-84-13	2. GOVT ACCESSION NO. AD-A148705	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) COMPRESSIVE STRENGTH-MATURITY RELATIONSHIPS OF MORTAR CONTAINING FLY ASH		5. TYPE OF REPORT & PERIOD COVERED Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Steven A. Ragan		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Engineer Waterways Experiment Station Structures Laboratory PO Box 631, Vicksburg, Mississippi 39180-0631		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS CWIS Work Unit 31138
11. CONTROLLING OFFICE NAME AND ADDRESS DEPARTMENT OF THE ARMY US Army Corps of Engineers Washington, DC 20314-1000		12. REPORT DATE October 1984
		13. NUMBER OF PAGES 38
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cement (LC)
Curing (LC)
Fly ash (LC)
Mortar--Additives--Testing (LC)
Strength of materials (LC)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The relationships between the compressive strength and maturity of four mortar mixtures containing fly ash were evaluated. The maturity of the mortar was determined using both the traditional maturity method proposed by Saul and the maturity-age procedure proposed by Freisleben-Hansen and Pedersen.

Two mortar mixtures had 25 percent of the cement by absolute volume replaced with Class F fly ash, and two mixtures had 35 percent by the cement of

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued).

absolute volume replaced with Class F fly ash. Twenty-four compressive strength specimens and three temperature monitoring specimens were fabricated from each batch and cured at the temperature of interest. The curing temperatures investigated included 40°, 73°, and 85° F, and a daily fluctuating temperature ranging from 40° to 80° F. The temperature-age history of the specimens was monitored continuously and compressive strength tests were conducted at various ages up to 28 days.

Both the classical maturity method proposed by Saul and the maturity-age procedure proposed by Freisleben-Hansen and Pedersen estimated the compressive strength of the test specimens with a degree of success. The maturity-age procedure resulted in less scatter about the regression lines than the classical method for mortar cured at 85° F and 40°-80° F. Less scatter of the classical maturity data was noted for mortar cured at 40° F.

Additional research is needed to determine if the maturity-age method for estimating compressive strength can be extended from mortar specimens to concrete test specimens and then to concrete in place in a structure.

PREFACE

This investigation was conducted at the Structures Laboratory (SL), U. S. Army Engineer Waterways Experiment Station (WES), under the sponsorship of the Headquarters, U. S. Army Corps of Engineers (HQUSACE), as a part of Civil Works Investigation Studies Work Unit 31138, "New Technologies for Testing and Evaluating Concrete." Mr. Fred Anderson of the Structures Branch, Engineering Division, Directorate of Engineering and Construction, HQUSACE, served as Technical Monitor.

The investigation was conducted under the general supervision of Mr. Bryant Mather, Chief, SL, and Mr. John Scanlon, Chief, Concrete Technology Division (CTD), SL, and under the direct supervision of Mr. Kenneth L. Saucier, Chief, Concrete and Evaluation Group, CTD, who also served as principal investigator. Messrs. Steven A. Ragan, Frank S. Stewart, and Dale Glass actively participated in the investigation, and Mr. Ragan prepared this report.

COL Tilford C. Creel, CE, was Commander and Director of WES during this investigation and the preparation and publication of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
inches	25.4	millimetres
pounds (force) per square inch	0.00689476	megapascals
pounds (mass) per cubic yard	0.59327642	kilograms per cubic metre

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

COMPRESSIVE STRENGTH-MATURITY RELATIONSHIPS OF MORTAR CONTAINING FLY ASH

PART I: INTRODUCTION

Background

1. Accelerated concrete construction schedules combined with the requirement to maintain structural safety have generated increased interest in methods used to estimate the strength of concrete in place in a structure. Civil Works Construction Guide Specification CW-03305 (Department of the Army 1978) requires that the duration of time for curing and protecting concrete used in civil works concrete construction projects be based on the type of cementitious materials in rather than the rate of strength development of the concrete. This requirement may result in unnecessarily long curing and protection periods if early concrete temperatures are near the upper limit of acceptability; or it may result in inadequate curing and protection if early concrete temperatures are at the lower level of acceptability.

2. Numerous methods for monitoring the strength of concrete in place in a structure have been proposed. These methods included (a) the rebound number, (b) pullout strength, (c) the penetration resistance, (d) the compressive strength of concrete cylinders cast in place in the structure, and (e) the compressive strength of field-cured cylinders. In addition, ACI Committee 306, Cold Weather Concreting (American Concrete Institute 1982), included the maturity method as an option for determining strength of concrete in the structure as a basis for safe protection removal. The strength of a properly consolidated and cured concrete mixture is dependent on its age-temperature history. In the early 1950's Saul (1951) proposed the concept of maturity to account for the time and temperature effects on concrete strength development. Saul defined maturity as the product of time and temperature of the concrete according to the equation:

$$M = \int (T - T_o)dt \qquad (1)$$

where

T = temperature of concrete

T_o = datum temperature below which concrete will not gain strength (generally accepted in North America as 14° F*)

Concrete samples having equal maturities, as defined above, should therefore have equal strengths regardless of the distinct time-temperature history each might have experienced. This traditional concept was validated by Bergstrom (1953) and Plowman (1956) and is currently advocated in the ACI Committee 306 report (American Concrete Institute 1982).

3. Klieger (1958) and, more recently, Carino and Lew (1983) published research findings which present significant limitations in the use of Saul's maturity method. They concluded that when the early-age-temperatures of samples of the same concrete are dissimilar, there is not a unique strength-maturity relation for the concrete. Freisleben-Hansen and Pedersen (1977) proposed a maturity function based on the principle that the strength of concrete at any age is related to the degree of hydration, where

$$\text{degree of hydration,} \quad \alpha = \frac{\text{quantity of hydrated cement}}{\text{original quantity of cement}} \tag{2}$$

The rate of hydration, $d\alpha/dt$, in a given cement paste and at a given degree of hydration, $g(\alpha)$, is a function, $f(T)$, of the temperature of the paste at the moment in question, i.e.,

$$\frac{d\alpha}{dt} = g(\alpha) \cdot f(T) \tag{3}$$

The above mentioned authors also proposed that the maturity function, $f(T)$, be based on the Arrhenius equation for thermal activation which can be evaluated from the following

$$f(T) = K \cdot \exp\left(- \frac{E}{R \cdot T_k}\right) \tag{4}$$

where

K = proportionality constant

E = activation energy, kjoules/mol

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* A table of factors for converting non-SI units of measurement to SI (metric) units is given on page 3.

R = universal gas constant

T_k = temperature, °k

Freisleben-Hansen and Pedersen (1977) reported that this function is applicable within a temperature range of 14° to 176° F. The activation energy is a function of cement chemical composition which must be empirically determined for each cement of interest. However, Copeland, Kantro, and Verbeck (1960) suggested that the same activation energy could be used for different cements having different chemical compositions. Freisleben-Hansen and Pedersen supported this observation and stated that the activation energy also had a temperature dependency. They proposed the following expression for this dependency:

$$E(T_F) = \frac{33.5 \text{ kjoules}}{\text{mol}} \text{ , when } T_F \geq 68° \text{ F} \tag{5}$$

and

$$E(T_F) = 62.9 - 0.817(T_F - 32) \frac{\text{kjoules}}{\text{mol}} \text{ , when } T_F < 68° \text{ F} \tag{6}$$

4. If the expression for the maturity function in Equation 4 is substituted into the differential Equation 3, the following equation results:

$$\frac{d\alpha}{dt} = Kg(\alpha) \exp\left(- \frac{E}{R \cdot T_k}\right) \tag{7}$$

An integration of Equation 7 is:

$$\int_0^\alpha \frac{d\alpha}{Kg(\alpha)} = \int_0^t \exp\left(- \frac{E}{R \cdot T_k}\right) dt \tag{8}$$

Since standard concrete specimens are cured at 73.4° ± 3° F, it is convenient to define a maturity age on the basis of 73.4° F. Maturity age can be defined as the age that a standard concrete test cylinder cured at 73.4° F must attain to achieve the same compressive strength as similar concrete cured at temperatures varying from 73.4° F. For a standard specimen cured at a constant temperature of 73.4° F, equal to 296° K, the rate of hydration becomes:

$$\frac{d\alpha}{dt} = Kg(\alpha) \exp\left(- \frac{E}{R \cdot 296}\right) \tag{9}$$

and integrating Equation 9 results in:

$$\int_0^\alpha \frac{d\alpha}{Kg(\alpha)} = \int_0^M \exp\left(-\frac{E}{R \cdot 296}\right) dt = M \exp\left(-\frac{E}{R \cdot 296}\right) \tag{10}$$

where M is the maturity age as defined above. The expression on the right side of Equation 10 is equal to the integral on the right side of Equation 8. Therefore,

$$\int_0^t \exp\left[-\frac{E}{R \cdot T_k(t)}\right] dt = M \exp\left(-\frac{E}{R \cdot 296}\right) \tag{11}$$

From Equation 11 the maturity age can be reduced to:

$$\begin{aligned} M &= \int_0^t \exp\left[\frac{E}{R \cdot 296} - \frac{E}{R \cdot T_k(t)}\right] dt \\ &= \int_0^t \exp\left(\frac{E}{R \cdot 296} - \frac{E}{R \cdot \frac{T_F + 459.67}{1.8}}\right) dt \end{aligned} \tag{12}$$

Byfors (1980) examined several maturity functions in an investigative study, including those proposed by Saul and by Freisleben-Hansen and Pedersen. Byfors also demonstrated that the latter study better accounted for the time-temperature effects on strength gain.

Purpose

5. The investigation reported herein evaluated the compressive strength-maturity relationships of mortar which contained fly ash and was cured at constant and at fluctuating temperatures. Mortar, rather than concrete, was selected for this study in order to eliminate the effects of coarse aggregate distribution on compressive strength. Fly ash was included as a component in the mortar since all known investigations to date have dealt with concrete or mortar containing only Type I or Type II portland cement. Both the traditional maturity method proposed by Saul and the maturity-age procedure proposed by Freisleben-Hansen and Pedersen were evaluated to determine if either approach could estimate compressive strength of mortar accurately.

Scope

6. The strength-maturity relationships of four mortar mixtures were

evaluated using the two maturity methods previously mentioned. Each mixture contained manufactured limestone sand, Type II portland cement, and Class F fly ash. Two mixtures had 25 percent of the cement by absolute volume replaced with fly ash, and two mixtures had 35 percent of the cement by absolute volume replaced with fly ash.

7. Four batches of each mixture were made. Twenty-four compressive strength specimens and three temperature monitoring specimens were fabricated from each batch and cured at the temperature of interest. The curing temperatures investigated were 40°, 73°, 85° F, and a daily fluctuating temperature ranging from 40° to 80° F. The temperature-age history of the specimens was monitored continuously, and compressive strength tests were conducted at various ages up to 28 days.

PART II: MATERIALS, MIXTURES, TEST PROCEDURE, AND TEST RESULTS

Materials

8. Table 1 gives the chemical and physical properties of the Type II portland cement (RC-867) that was used. The chemical and physical properties of the Class F fly ash (AD-590) are given in Table 2. The physical properties and the grading of the manufactured limestone fine aggregate (CL-2 MS-1) are shown in Table 3.

Mixtures

9. The following four mortar mixtures were proportioned and used to evaluate the two maturity methods:

Mixture No.	Water-Cement Ratio by Mass	Cementitious Content lb/yd^3	Fly Ash Replacement percent
1	0.50	779.8	25
2	0.60	650.0	25
3	0.60	649.3	35
4	0.70	557.0	35

The proportions for each mixture are given in Table 4.

Test Procedure

10. The curing temperatures used in this investigation included 40°, 73°, and 85° F and a daily fluctuating temperature ranging from 40° to 80° F. The fluctuating temperature curing began at 40° F. When molding of the test specimens was completed, temperature control for the curing room was immediately switched to heat. After approximately 8 hr, the temperature control was automatically switched to cold for 15 hr. This time cycle was closely followed for the entire 28 days the temperatures were monitored. Approximately 4 hr were required for the ambient temperature to reach the maximum of 80° F after the control was switched to heat each day. Eight hours were required to bring the ambient temperature back to 40° F when the control was reset to cold.

11. The mortar materials were stored at each temperature investigated for approximately 5 days prior to mixing. Each batch of mortar was machine mixed according to applicable portions of ASTM C 192 (ASTM 1983). Following mixing, the mortar was immediately taken into a curing room set at the designated curing temperature where test specimens were fabricated. Twenty-four compressive strength specimens and three temperature monitoring specimens were made from each batch. All specimens were 6-in.-diam by 12-in.-high cylinders, and the concrete was compacted by rodding according to applicable sections of ASTM C 192. The test specimens were demolded within 24 to 48 hr after fabrication and were placed in individual polyethylene bags which contained enough lime-saturated water to inundate the specimens. The test specimens were cured using this technique to ensure that no drying of the mortar would occur and to reduce the specimen temperature lag associated with curing in larger volumes of water.

12. Copper-constantan thermocouples were embedded approximately 2 in. from the top of each temperature monitoring specimen. The ambient and mortar temperatures were continuously monitored and recorded at 15-min intervals from the time of specimen fabrication until all compressive strength tests were completed. The age and temperature data were collected by a datalogger and were input to a computer so that maturity values and maturity ages could be calculated. Compressive strength tests were conducted on three specimens each at eight test ages ranging from 1 to 28 days.

Test Results

13. The average compressive strength test results of each mixture are given in Table 5. The relationships between compressive strength and age of mortar for each temperature investigated are shown in Figures 1-4. The maturity and maturity-age values corresponding to the specimen test ages are also shown in Table 5. The compressive strength versus maturity relationships and compressive strength versus maturity-age relationships are shown in Figures 5-8 and Figures 9-12, respectively.

PART III: DISCUSSION OF TEST RESULTS

14. The compressive strength versus age curves (Figures 1-4) indicate that the compressive strength of the mortar at any age is a function of the curing temperature. In general, higher initial curing temperatures result in greater compressive strengths for each mixture at any selected age. Kleiger (1958) suggested that one might expect a reversal of this trend at later ages. The relationship between the 40° F and 40°-80° F curves of mixture 4 (Figure 4) is unexpected. Greater compressive strengths are noted for the 40° F cured mortar than the 40°-80° F cured mortar at ages later than approximately 120 hr. Batch variations in the mortar mixture proportions or some unintended drying of the 40°-80° F specimens may account for this relationship.

15. Table 5 gives an indication of the strength range at each age for each mixture. The strength range of a mixture is defined as the difference between the largest and smallest compressive strength at the test age of interest. The average strength range of the four mixtures at 7 days age is 834 psi; at 14 days age is 1053 psi; at 21 days age is 1527 psi; and at 28 days age is 1788 psi. These large variations in compressive strength demonstrate the marked effect of temperature on the strength gain of the mortar.

16. The compressive strength versus maturity data of the four mixtures are plotted in Figures 5-8. Each figure shows a least squares fit of 73° F data with a best-fit curve determined using a general purpose statistical analysis and curve fitting computer program (Renner 1979). The curves serve as a basis for estimating the compressive strength of mortar cured at the previously mentioned temperatures. The best-fit curve of each mixture is a logistic curve whose general equation is as follows:

$$Y = A_1 + A_2 x + A_3 \log x \qquad (13)$$

where

Y = predicted compressive strength of mortar, psi

A_1, A_2, and A_3 = regression coefficients

x = maturity, °F · hr

17. Table 6 compares the actual compressive strengths of each mixture with those estimated by the compressive strength versus maturity regression equation given for each mixture. The differences between the actual and

estimated compressive strengths, or the residuals, are also given. In general, the largest residuals for each mixture occur in those specimens cured at the fluctuating 40°-80° F.

18. The compressive strength versus maturity-age data of the four mortar mixtures are plotted in Figures 9-12. A best-fit curve is again shown through the 73° F data, and again each curve has an equation whose general form is that of Equation 13. The compressive strengths estimated from these equations are shown in Table 7, along with the actual compressive strengths and the residuals. Generally, the largest residuals for each mixture occurred in these specimens cured at 40° F.

19. Table 8 summarizes the standard errors of estimates of compressive strength on maturity and compressive strength on maturity age for each mortar mixture. Each curing condition is examined. The standard error of estimate serves as a measure of the scatter about the regression line of Y on X , or in this case, compressive strength on maturity and compressive strength on maturity age. It is computed from the equation:

$$S.E._{YX} = \sqrt{\frac{\Sigma\left(Y - Y_{EST}\right)^2}{N}} \tag{14}$$

where

$S.E._{YX}$ = standard error of estimate of Y or X
Y = actual compressive strength, psi
Y_{EST} = estimated compressive strength, psi
$Y - Y_{EST}$ = residual compressive strength, psi
N = number of tests

The standard errors of estimate of compressive strength on maturity age are generally smaller than those of compressive strength on maturity for mortar cured at 85° F and 40°-80° F. Therefore, the maturity-age data of mortar cured at these temperatures generally fit their respective regression lines better than the maturity data fit their lines. Conversely, the standard errors of estimate of compressive strength on maturity are generally smaller than those of compressive strength on maturity age for mortar cured at 40° F. The latter result may be due to use of an inappropriate activation energy as shown in Equation 12. That is, the activation energy computed from Equation 6 may not be accurate when a mixture containing this cement is isothermally

cured at 40° F. Carino (1983) suggested that the activation energies computed from the equations proposed by Freisleben-Hansen and Pedersen might not truly represent all cements over a wide range of temperatures. Carino (1983) recommended a relatively simple testing procedure for determining the activation energy of a particular cement over a desired temperature range.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

20. Results of this investigation indicate that both the classical maturity method proposed by Saul and the maturity-age procedure proposed by Freisleben-Hansen and Pedersen can, with a degree of success, estimate the compressive strength from 1 to 28 days age of test specimens made from mortar containing fly ash.

21. The maturity-age procedure resulted in less scatter of the data about the regression lines than the classical maturity method for mortar cured at 85° F and 40°-80° F. Less scatter of the classical maturity data was noted for mortar cured at 40° F. This may be due to a possible erroneous activation energy used for calculating the maturity ages of mortar cured at 40° F.

22. Additional investigative studies are needed to discover if the activation energies for a variety of cementitious materials over a range of temperatures can be simply and accurately determined. Additional research is also needed to determine if the maturity-age method for estimating concrete compressive strength can be extended from mortar specimens to concrete test specimens and to concrete in place in a structure.

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Table 1

Chemical and Physical Properties of Type II Portland Cement, RC-867

Chemical Analysis Results, %	
SiO_2	21.8
Al_2O_3	4.5
Fe_2O_3	5.1
CaO	63.3
MgO	0.9
SO_3	2.1
Ignition loss	1.3
Insoluble residue	0.23
Na_2O	0.16
K_2O	0.38
Total alkali, as Na_2O	0.41
C_3S	49
C_2S	25
C_3A	4
C_4AF	15
Physical Properties	
Fineness, air permeability, cm^2/g	3700
Compressive strength, psi	
3 days	2200
7 days	3030
Autoclave expansion, percent	0.00
Initial setting time, hr:min	3:00
Final setting time, hr:min	5:00

Table 2

Chemical and Physical Properties of Fly Ash, AD-590

Chemical Analysis Results, %	
$SiO_2 + Al_2O_3 + Fe_2O_3$	88.0
MgO	1.3
SO_3	0.7
Available alkalies, as Na_2O	0.65
Moisture content	0.5
Ignition loss	2.0
Physical Properties	
Fineness, 45-μm (No. 325) sieve, percent retained	21
Specific gravity	2.43
Lime-pozzolan strength, psi, 7 days	1120
Autoclave expansion, percent	0.03

Table 3

Physical Properties and Gradings of Manufactured Fine Aggregate, CL-2 MS-1

Test	
Bulk specific gravity, saturated surface-dry	2.70
Absorption, %	0.9
Sieve Size	**Cumulative % Passing**
4.75 mm (No. 4)	100
2.36 mm (No. 8)	91
1.18 mm (No. 16)	55
600 μm (No. 30)	30
300 μm (No. 50)	13
150 μm (No. 100)	5
75 μm (No. 200)	3

Table 4

Mixture Proportions

Mixture No.	Measurement	Material: Portland Cement	Fly Ash	Fine Aggregate	Water	Air (Assumed)	Total
1	Solid volume, ft^3	3.156	1.052	15.734	6.248	0.810	27.000
	Bulk density, saturated surface-dry, lb/yd^3	620.3	159.5	2650.9	389.9		3820.6
2	Solid volume, ft^3	2.630	0.877	16.433	6.250	0.810	27.000
	Bulk density, saturated surface-dry, lb/yd^3	517.0	133.0	2768.6	390.0		3808.6
3	Solid volume, ft^3	2.234	1.257	16.355	6.244	0.810	27.000
	Bulk density, saturated surface-dry, lb/yd^3	458.7	190.6	2755.5	389.6		3794.4
4	Solid volume, ft^3	2.002	1.078	16.862	6.248	0.810	27.000
	Bulk density, saturated surface-dry, lb/yd^3	393.5	163.5	2840.9	389.9		3787.8

Table 5

Average Compressive Strengths

Mixture No.	Curing Temperature °F	Age Days	Age (hr)	Average Compressive Strength, psi	Maturity °F-hr	Maturity Age hr
1	40	2	(48)	390	1,569	13
		3	(72)	793	2,299	20
		4	(96)	1143	3,038	25
		7	(172)	1853	5,360	44
		10	(244)	2293	7,581	62
		14	(340)	2773	10,532	86
		21	(508)	3323	15,677	127
		28	(676)	3630	20,734	167
	73	1	(24)	545	1,648	24
		2	(48)	1368	3,193	48
		3	(72)	1861	4,702	72
		7	(172)	2876	11,307	172
		10	(244)	3355	15,832	244
		14	(340	3840	21,811	340
		21	(508)	4472	32,341	508
		28	(676)	4970	42,903	676
	85	1	(24)	973	2,088	37
		2	(48)	1600	3,713	70
		3	(72)	2040	5,583	102
		7	(172)	3140	12,823	240
		10	(244)	3647	18,527	339
		14	(340)	4093	25,761	473
		21	(508)	5123	38,458	708
		28	(676)	5680	51,386	1053
	40-80	1	(24)	203	1,121	14
		2	(48)	870	2,363	32
		3	(72)	1290	3,491	47
		7	(172)	2263	7,932	101
		9	(222)	2593	10,181	131
		14	(340)	3230	15,857	208
		21	(508)	3653	23,527	303
		28	(676)	4203	30,733	392
2	40	2	(48)	240	1,556	13
		3	(72)	493	2,308	19
		4	(96)	723	3,040	25
		7	(172)	1183	5,270	45
		10	(244)	1593	7,523	64
		15	(364)	1870	11,173	95
		21	(508)	2043	15,635	133
		28	(676)	2370	20,682	176
	73	1	(24)	446	1,639	24
		2	(48)	1032	3,177	48
		3	(72)	1370	4,681	72
		7	(172)	2089	11,281	172

(Continued)

Table 5 (Continued)

Mixture No.	Curing Temperature °F	Age Days	Age (hr)	Average Compressive Strength, psi	Maturity °F-hr	Maturity Age hr
2 (Continued)	73 (Continued)	10	(244)	2427	15,800	244
		14	(340)	2852	23,265	340
		21	(508)	3234	32,287	508
		28	(676)	3596	42,880	676
	85	1	(24)	650	1,865	36
		2	(48)	1057	3,667	69
		3	(72)	1400	5,543	102
		7	(172)	2010	12,988	241
		10	(244)	2417	18,428	342
		14	(340)	3090	27,519	511
		21	(508)	3713	38,487	716
		28	(676)	4050	51,277	955
	40-80	1	(24)	120	1,123	15
		2	(48)	497	2,366	32
		3	(72)	777	3,472	47
		7	(172)	1337	7,915	102
		10	(244)	1563	11,240	145
		14	(340)	2010	16,909	221
		21	(508)	2390	23,260	300
		28	(676)	2630	30,440	387
3	40	2	(48)	233	1,551	13
		3	(72)	473	2,309	20
		4	(96)	653	3,187	33
		8	(196)	1095	6,291	59
		10	(244)	1329	7,770	71
		14	(340)	1642	10,701	94
		21	(508)	1865	15,766	134
		28	(676)	2020	20,798	174
	73	1	(24)	303	1,636	24
		2	(48)	671	3,187	48
		3	(72)	908	4,723	72
		7	(172)	1487	11,063	172
		10	(244)	1773	15,625	244
		14	(340)	2084	21,725	340
		21	(508)	2472	34,959	508
		28	(676)	2882	45,646	676
	85	1	(24)	517	1,873	36
		2	(48)	890	3,612	68
		3	(72)	1100	5,438	101
		7	(172)	1727	13,075	329
		10	(244)	2070	18,385	424
		14	(340)	2507	25,486	554
		21	(508)	3297	37,927	781
		28	(676)	3857	50,342	1008

(Continued)

(Sheet 2 of 3)

Table 5 (Concluded)

Mixture No.	Curing Temperature °F	Age Days	Age (hr)	Average Compressive Strength, psi	Maturity °F-hr	Maturity Age hr
3 (Continued)	40-80	1	(24)	87	1,088	14
		2	(48)	403	2,303	31
		3	(72)	570	3,402	45
		7	(172)	1037	7,819	100
		9	(216)	1197	9,772	125
		14	(340)	1517	15,761	206
		21	(508)	1860	23,183	299
		28	(676)	2127	30,372	387
4	40	2	(48)	147	1,536	13
		3	(72)	297	2,290	19
		4	(96)	443	3,036	25
		7	(172)	893	5,355	44
		10	(244)	1107	7,601	62
		14	(340)	1333	10,515	85
		21	(508)	1577	15,567.1	125
		28	(696)	1753	20,608	165
	73	1	(24)	203	1,600	24
		2	(48)	498	3,152	48
		3	(72)	670	4,683	72
		7	(172)	1113	10,998	172
		10	(244)	1323	15,551	244
		14	(340)	1551	21,646	340
		21	(508)	1888	32,344	508
		28	(676)	2181	43,037	676
	85	1	(24)	357	1,857	35
		2	(48)	653	3,655	68
		3	(72)	833	5,457	101
		7	(172)	1227	12,850	237
		10	(244)	1443	18,238	335
		14	(340)	1873	25,378	466
		21	(508)	2447	37,870	695
		28	(676)	2990	50,341	923
	40-80	1	(24)	60	1,059	13
		2	(48)	257	2,290	31
		3	(72)	380	3,413	46
		7	(172)	773	7,824	100
		9	(216)	813	9,801	125
		14	(340)	1050	15,761	143
		21	(508)	1247	23,179	298
		28	(676)	1407	30,370	385

(Sheet 3 of 3)

Table 6

Compressive Strength Residuals Based on Strength-Maturity Data

Curing Temperature °F	Maturity °F-hr	Actual Compressive Strength, Y psi	Estimated Compressive Strength, Y_{EST} psi	Residual $Y - Y_{EST}$ psi
		Mixture 1, 73° F Regression Line		
		$Y = 7778.109 + 0.0176x + 2588.310 (\log x)$		
40	1,569	390	520	-130
	2,299	793	963	-170
	3,038	1143	1289	-146
	5,360	1853	1969	-116
	7,581	2293	2397	-104
	10,532	2773	2819	-46
	15,677	3323	3357	-34
	20,734	3630	3760	-130
85	2,088	973	851	122
	3,713	1600	1527	73
	5,583	2040	2018	22
	12,823	3140	3081	59
	18,527	3647	3595	52
	25,761	4093	4093	0
	38,458	5123	4767	356
	51,386	5680	5321	359
40-80	1,121	203	135	68
	2,363	870	995	-125
	3,491	1290	1454	-164
	7,932	2263	2454	-191
	10,181	2593	2775	-182
	15,857	3230	3373	-143
	23,527	3653	3951	-298
	30,733	4203	4379	-176
		Mixture 2, 73° F Regression Line		
		$Y = 5347.402 + 0.0138x + 1803.302 (\log x)$		
40	1,556	240	430	-190
	2,308	493	749	-256
	3,040	723	975	-252
	5,270	1183	1437	-254
	7,523	1593	1746	-153
	11,173	1870	2106	-236
	15,635	2040	2431	-388
	20,682	2370	2719	-349

(Continued)

(Sheet 1 of 3)

Table 6 (Continued)

Curing Temperature °F	Maturity °F-hr	Actual Compressive Strength, Y psi	Estimated Compressive Strength, Y_{EST} psi	Residual $Y - Y_{EST}$ psi
		Mixture 2, 73° F Regression Line		
		$Y = 5347.402 + 0.0138x + 1803.302 (\log x)$ (Continued)		
85	1,865	650	576	74
	3,667	1057	1131	-74
	5,543	1400	1480	-80
	12,988	2010	2249	-239
	18,428	2417	2598	-181
	27,519	3090	3037	53
	38,487	3713	3451	262
	51,277	4050	3851	199
40-80	1,123	120	169	-49
	2,366	497	769	-272
	3,472	777	1085	-308
	7,915	1337	1792	-455
	11,240	1563	2112	-549
	16,909	2010	2510	-500
	23,260	2390	2847	-457
	30,440	2630	3156	-526
		Mixture 3, 73° F Regression Line		
		$Y = 3775.702 + 0.0170x + 1256.600 (\log x)$		
40	1,551	233	200	-27
	2,309	473	490	-17
	3,187	653	680	-27
	6,291	1095	1105	-10
	7,770	1329	1245	84
	10,701	1642	1470	172
	15,766	1865	1768	97
	20,798	2020	2005	15
85	1,873	517	368	149
	3,612	890	757	133
	5,438	1100	1011	89
	13,075	1727	1620	107
	18,385	2070	1896	174
	25,486	2507	2196	311
	37,927	3297	2625	672
	50,342	3857	2989	868
40-80	1,088	87	59	28
	2,303	403	489	-86
	3,402	570	720	-150
	7,819	1037	1250	-213

(Continued)

(Sheet 2 of 3)

Table 6 (Concluded)

Curing Temperature °F	Maturity °F-hr	Actual Compressive Strength, Y psi	Estimated Compressive Strength, Y_{EST} psi	Residual $Y - Y_{EST}$ psi
		Mixture 3, 73° F Regression Line		
		$Y = 3775.702 + 0.0170x + 1256.600 (\log x)$ (Continued)		
40-80 (Continued)	9,772	1197	1405	-208
	15,761	1517	1768	-251
	23,183	1860	2105	-245
	30,372	2127	2375	-248
		Mixture 4, 73° F Regression Line		
		$Y = 2686.852 + 0.0168x + 893.992 (\log x)$		
40	1,536	147	188	-41
	2,290	297	355	-58
	3,036	443	477	-34
	5,355	893	737	156
	7,601	1107	910	197
	10,515	1333	1036	247
	15,567	1577	1322	255
	20,608	1753	1517	236
85	1,857	357	267	90
	3,655	653	560	93
	5,457	833	746	87
	12,850	1227	1203	24
	18,238	1443	1429	14
	25,378	1873	1678	195
	37,870	2447	2043	404
	50,341	2990	2362	628
40-80	1,059	60	35	25
	2,290	257	355	-98
	3,413	380	529	-149
	7,824	773	925	-152
	9,801	813	1046	-233
	15,761	1050	1331	-281
	23,179	1247	1605	-358
	30,370	1407	1831	-424

(Sheet 3 of 3)

Table 7

Compressive Strength Residuals Based on Strength-Maturity Age Data

Curing Temperature °F	Maturity Age °F-hr	Actual Compressive Strength, Y psi	Estimated Compressive Strength, Y_{EST} psi	Residual $Y - Y_{EST}$ psi
Mixture 1, 73° F Regression Line				
$Y = -2962.526 + 1.1149x + 2536.412 (\log x)$				
40	13	390	-89	479
	20	793	337	456
	25	1143	629	514
	44	1853	1263	590
	62	2293	1653	640
	86	2773	2039	734
	127	3323	2516	807
	167	3630	2862	768
85	37	973	1069	-96
	70	1600	1800	-200
	102	2040	2251	-211
	240	3140	3339	-199
	339	3647	3834	-187
	473	4093	4349	-256
	708	5123	5055	68
	1053	5680	5878	-198
40-80	14	203	-64	267
	32	870	877	-7
	47	1290	1324	-34
	101	2263	2236	27
	131	2593	2557	78
	208	3230	3152	-15
	303	3653	3668	152
	392	4203	4051	36
Mixture 2, 73° F Regression Line				
$Y = -2000.571 + 0.8691x + 1769.891 (\log x)$				
40	13	240	-24	264
	19	493	275	218
	25	723	508	215
	45	1183	968	215
	64	1593	1251	342
	95	1870	1583	287
	139	2040	1911	132
	176	2370	2128	242

(Continued)

Table 7 (Continued)

Curing Temperature °F	Maturity Age °F-hr	Actual Compressive Strength, Y psi	Estimated Compressive Strength, Y_{EST} psi	Residual $Y - Y_{EST}$ psi
		Mixture 2, 73° F Regression Line		
		$Y = -2000.571 + 0.8691x + 1769.891 (\log x)$ (Continued)		
85	36	650	779	-129
	69	1057	1314	-257
	102	1400	1646	-246
	241	2010	2426	-416
	342	2417	2783	-366
	511	3090	3238	-148
	716	3713	3675	38
	955	4050	4104	-54
40-80	15	120	73	47
	32	497	699	-202
	47	777	993	-216
	102	1337	1645	-308
	145	1563	1953	-390
	221	2010	2340	-330
	300	2390	2644	-254
	387	2630	2916	-286
		Mixture 3, 73° F Regression Line		
		$Y = -1336.498 + 1.3764x + 1158.705 (\log x)$		
40	13	233	-24	257
	20	473	185	288
	33	653	475	178
	59	1095	794	425
	71	1329	904	562
	94	1642	1080	551
	134	1865	1314	522
	174	2020	1498	301
85	36	517	510	7
	68	890	884	6
	101	1100	1124	-24
	329	1727	2032	-305
	424	2070	2292	-222
	554	2507	2604	-97
	781	3297	3090	207
	1008	3857	3531	326
40-80	14	87	-1	88
	31	403	429	-26
	45	570	641	-71
	100	1037	1119	-82

(Continued)

(Sheet 2 of 3)

Table 7 (Concluded)

Curing Temperature °F	Maturity Age °F-hr	Actual Compressive Strength, Y psi	Estimated Compressive Strength, Y_{EST} psi	Residual $Y - Y_{EST}$ psi
Mixture 3, 73° F Regression Line				
$Y = -1336.498 + 1.3764x + 1158.705 (\log x)$ (Continued)				
40-80 (Continued)	125	1197	1263	-111
	206	1517	1628	-83
	299	1860	1943	-66
	387	2127	2193	-66
Mixture 4, 73° F Regression Line				
$Y = -1023.387 + 1.0928x + 870.957 (\log x)$				
40	13	147	-33	180
	19	297	113	184
	25	443	225	218
	44	893	459	434
	62	1107	607	500
	85	1333	752	581
	125	1577	940	637
	165	1753	1088	665
85	35	357	362	5
	68	653	650	3
	101	833	833	0
	237	1227	1303	-76
	335	1443	1542	-99
	466	1873	1810	63
	695	2447	2211	236
	923	2990	2568	422
40-80	13	60	-27	87
	31	257	308	-51
	46	380	471	-91
	100	773	829	-56
	125	813	941	-128
	143	1050	1010	40
	298	1247	1457	-210
	385	1407	1650	-243

(Sheet 3 of 3)

Table 8

Standard Error of the Estimates of Compressive Strength on Maturity and Maturity Age

Mixture No.	Curing Temperature °F	Standard Error of Compressive Strength on Maturity, psi	Standard Error of Compressive Strength on Maturity Age, psi
1	40	118	636
	85	188	186
	40-80	179	114
2	40	270	246
	85	165	244
	40-80	421	272
3	40	78	410
	85	417	194
	40-80	195	78
4	40	177	466
	85	279	178
	40-80	249	134

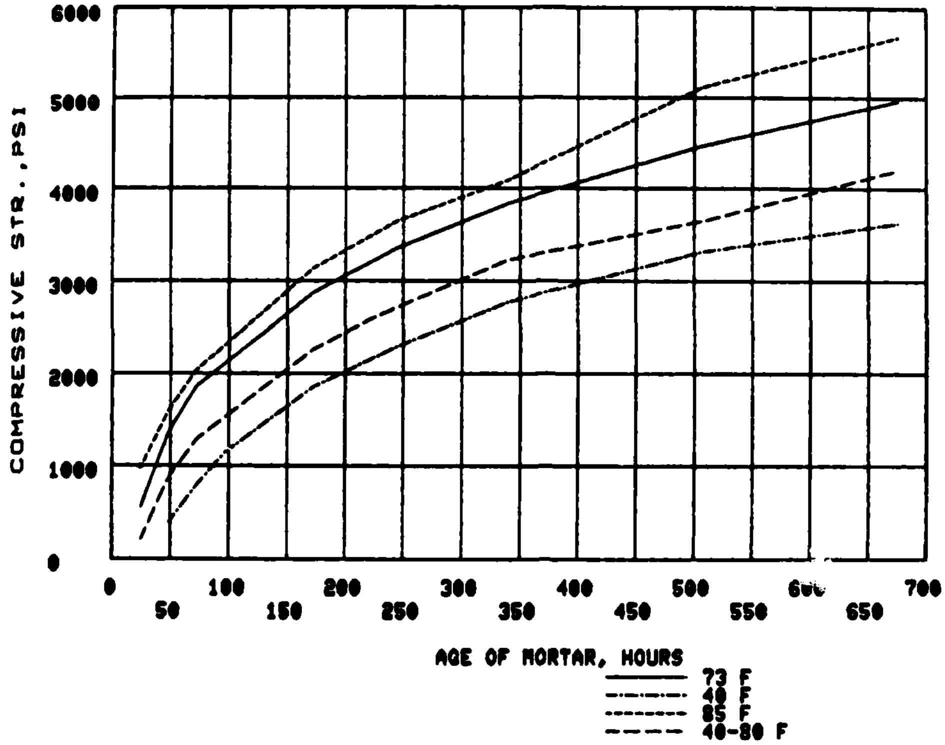


Figure 1. Relationship between compressive strength and age of mortar, mixture 1

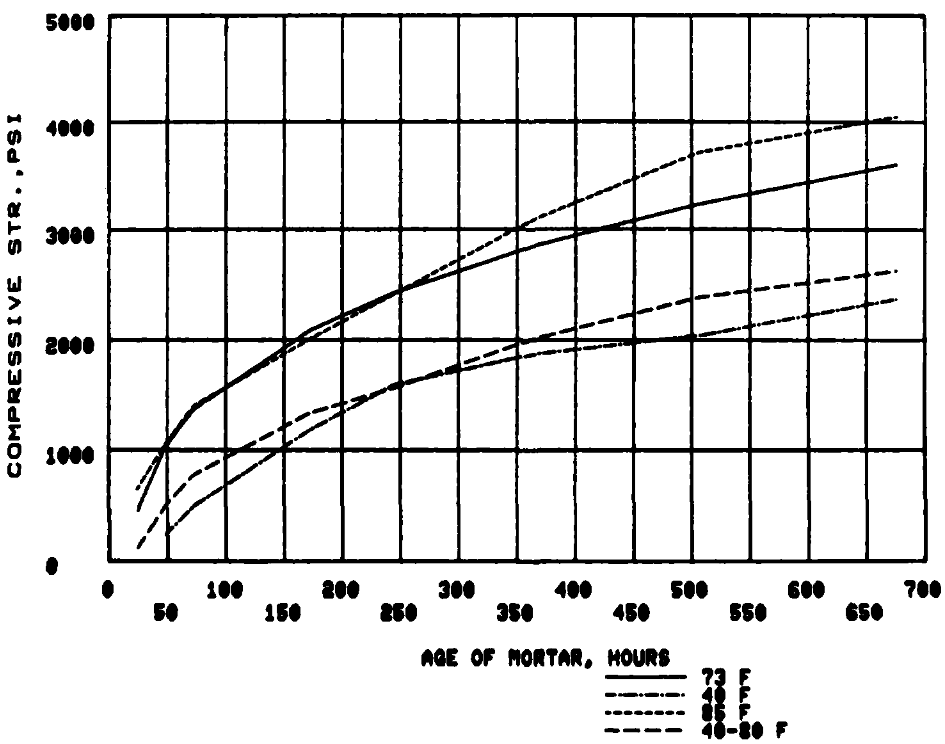


Figure 2. Relationship between compressive strength and age of mortar, mixture 2

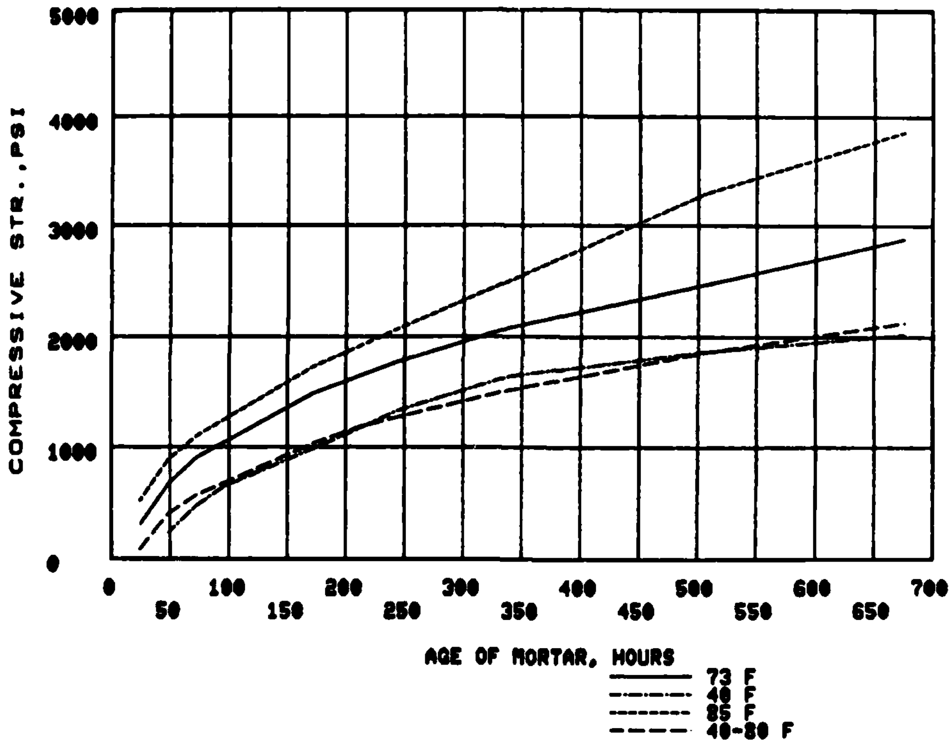


Figure 3. Relationship between compressive strength and age of mortar, mixture 3

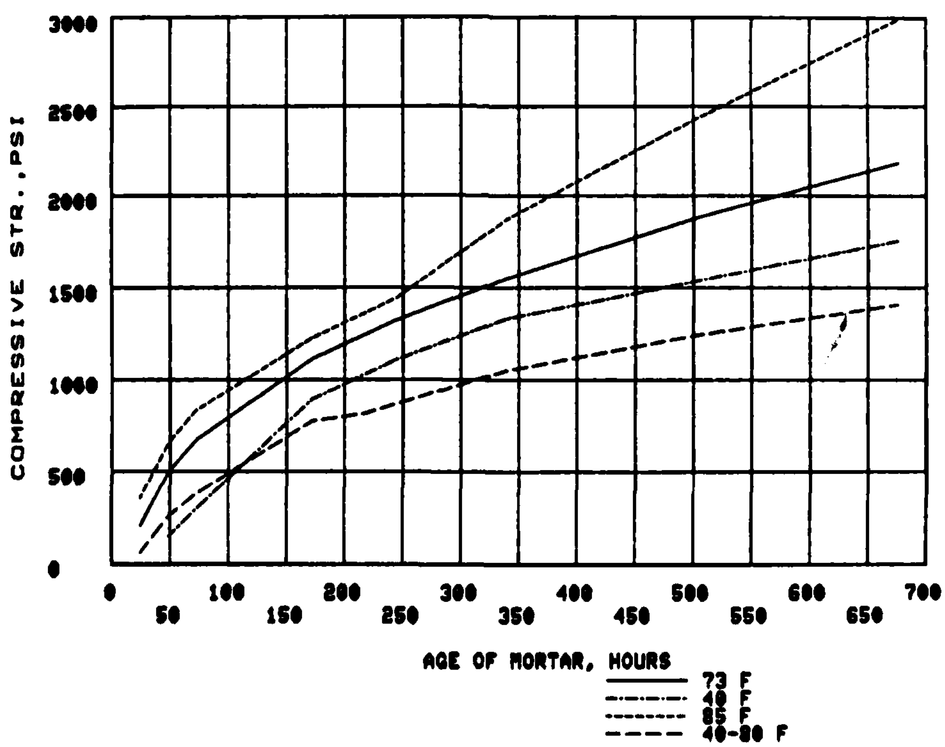
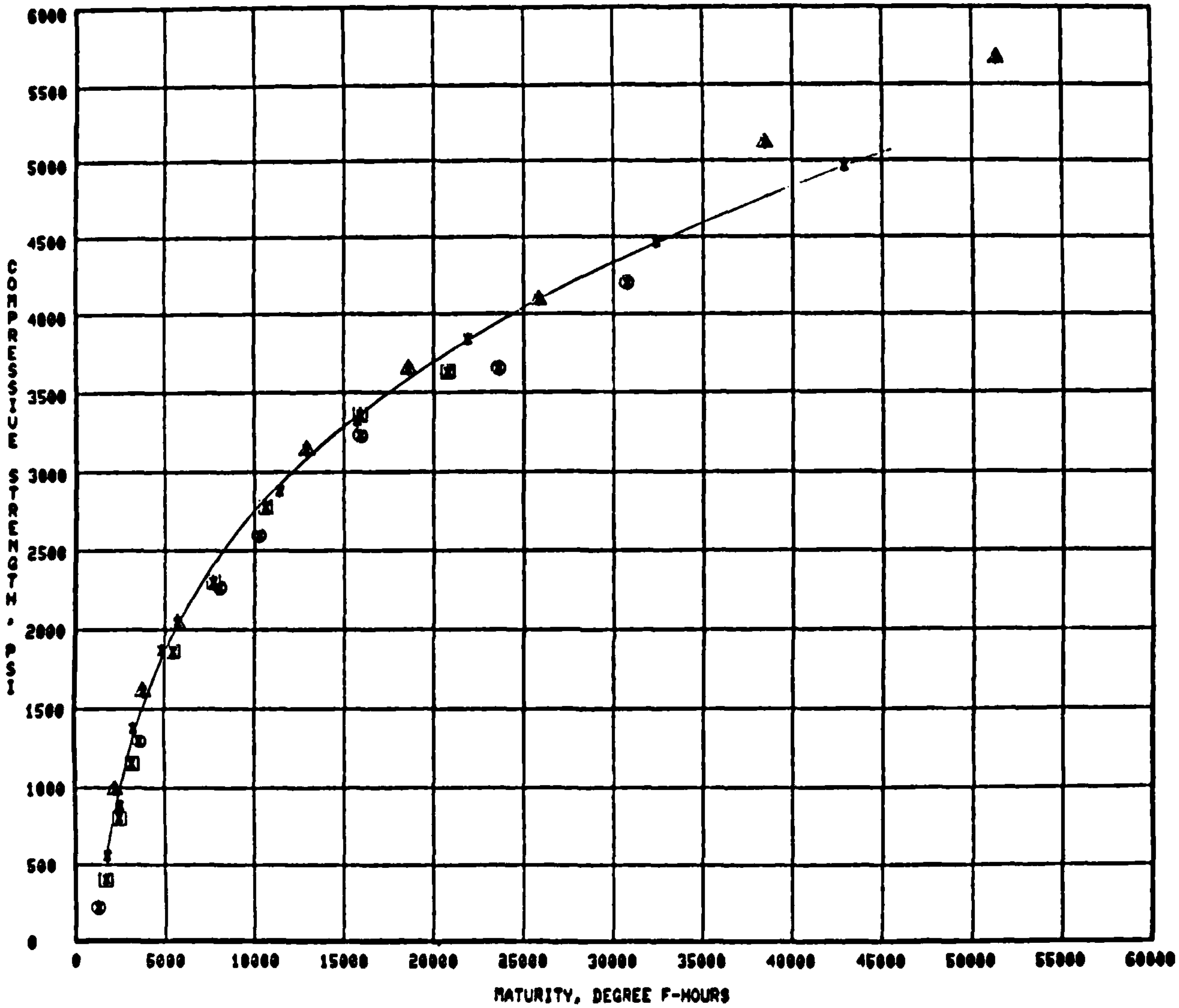


Figure 4. Relationship between compressive strength and age of mortar, mixture 4



* - 73° F ⊠ - 40° F ⚠ - 85° F ⊛ - 40-80° F

Figure 5. Relationship between compressive strength and maturity of mortar, mixture 1

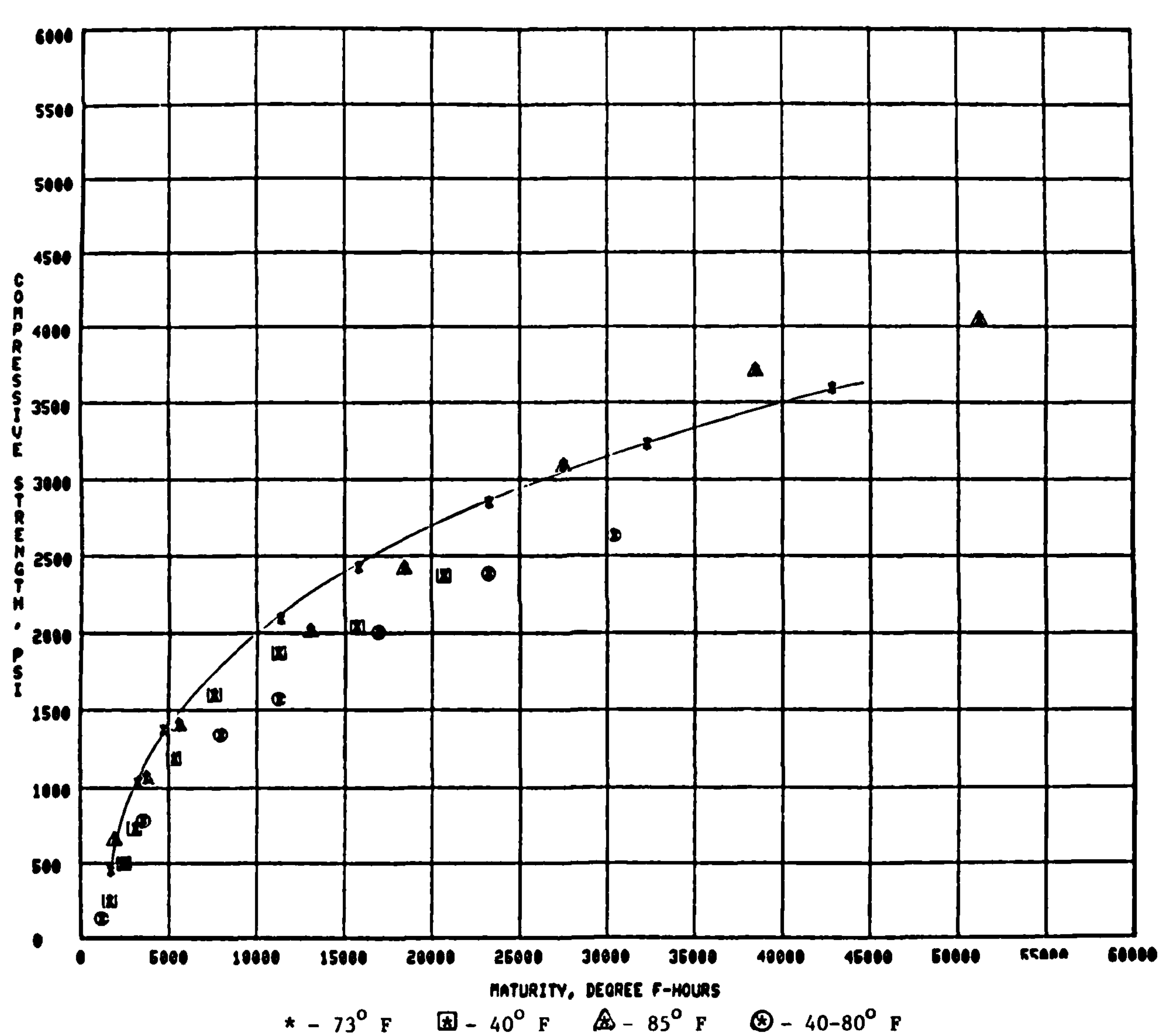


Figure 6. Relationship between compressive strength and maturity of mortar, mixture 2

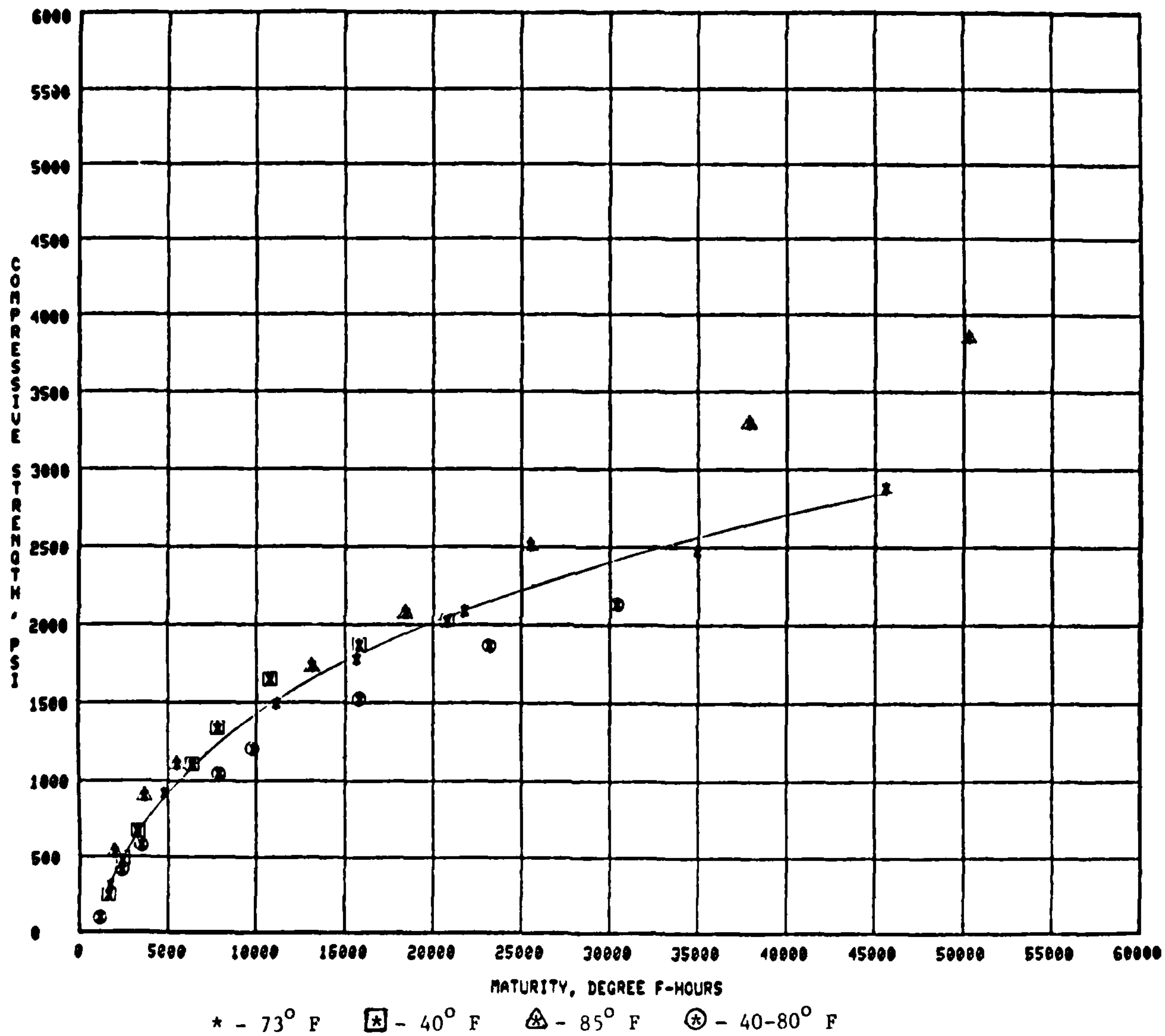
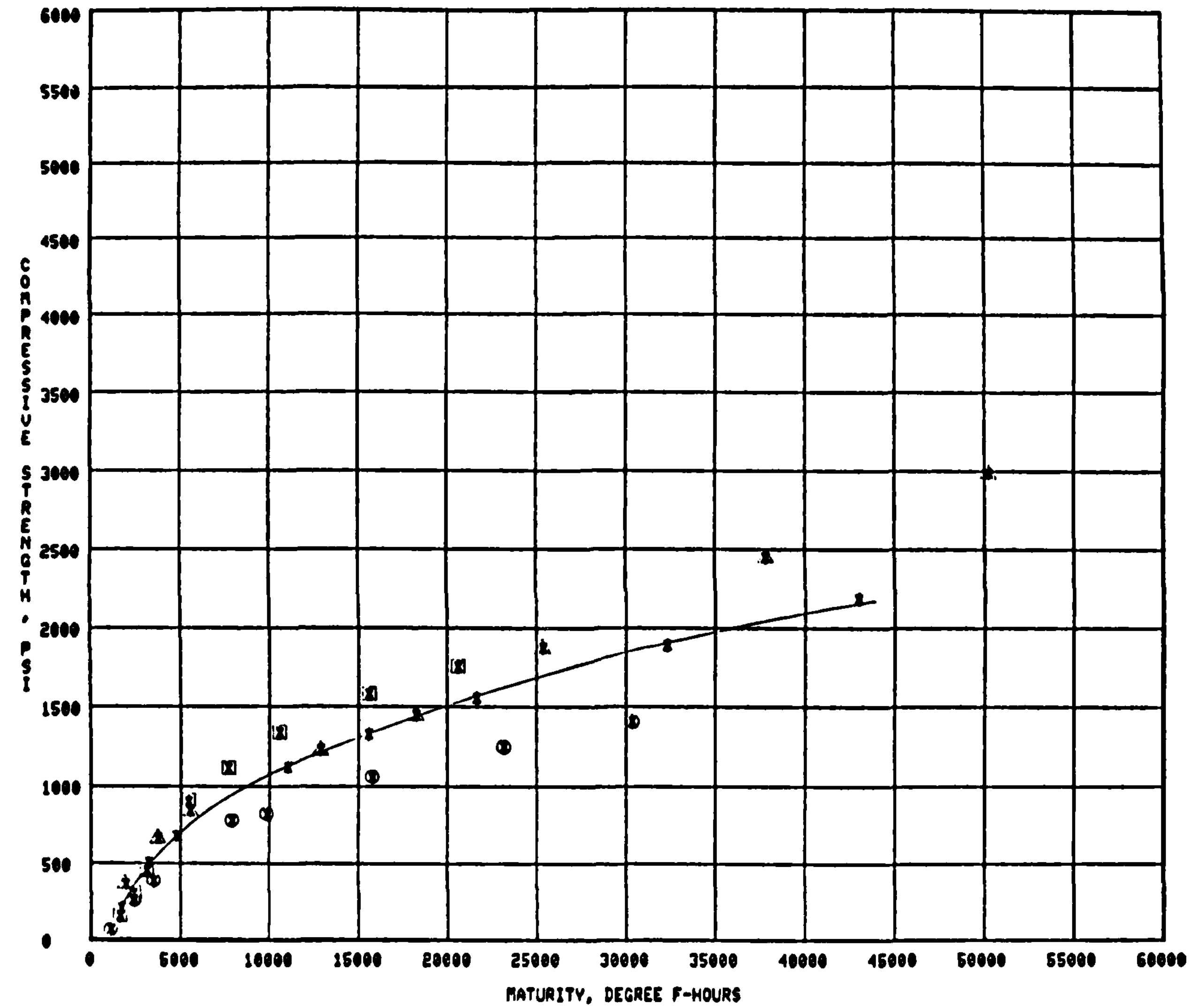


Figure 7. Relationship between compressive strength and maturity of mortar, mixture 3



* - 73° F ⊡ - 40° F △ - 85° F ⊛ - 40-80° F

Figure 8. Relationship between compressive strength and maturity of mortar, mixture 4

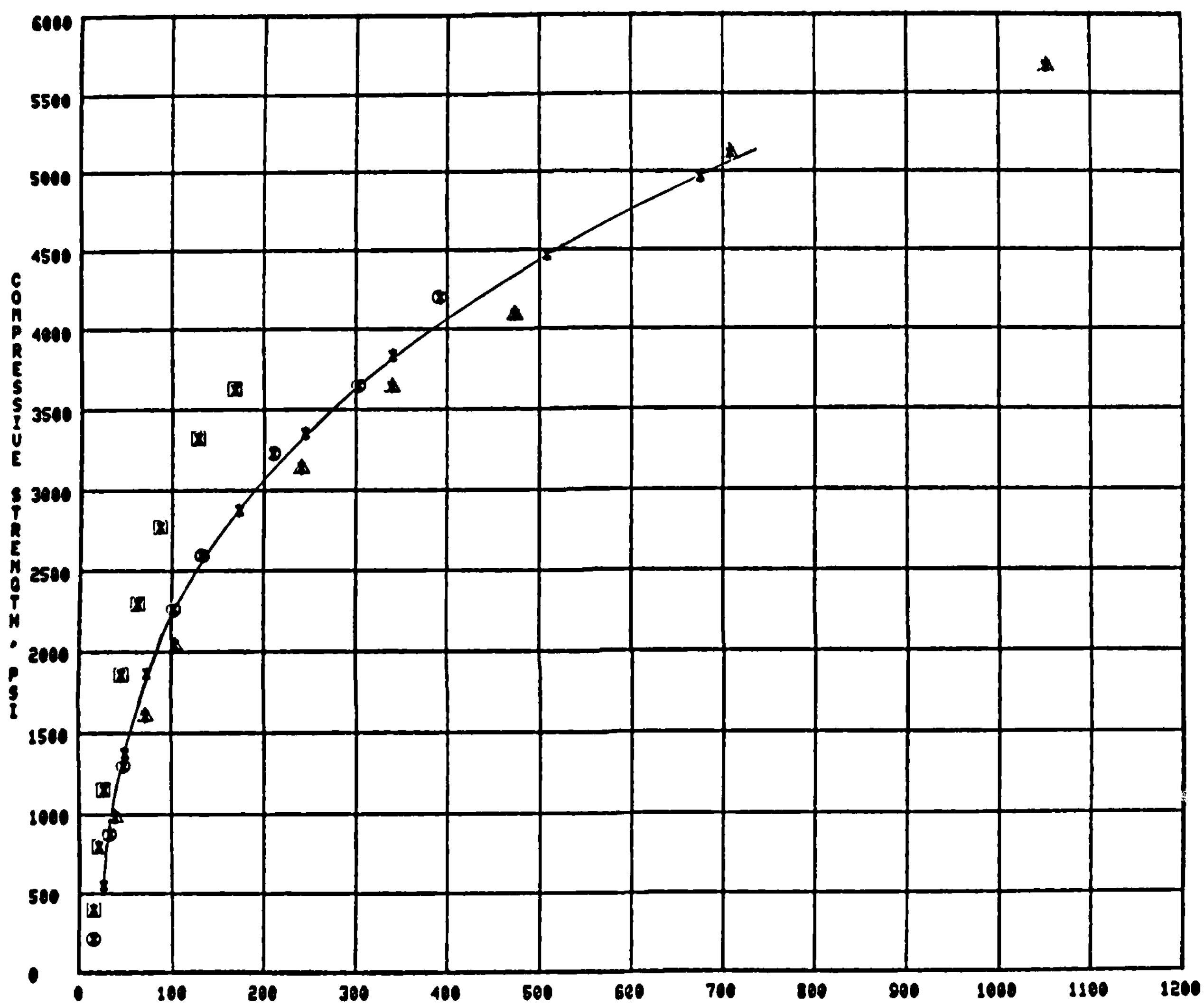


Figure 9. Relationship between compressive strength and maturity age of mortar, mixture 1

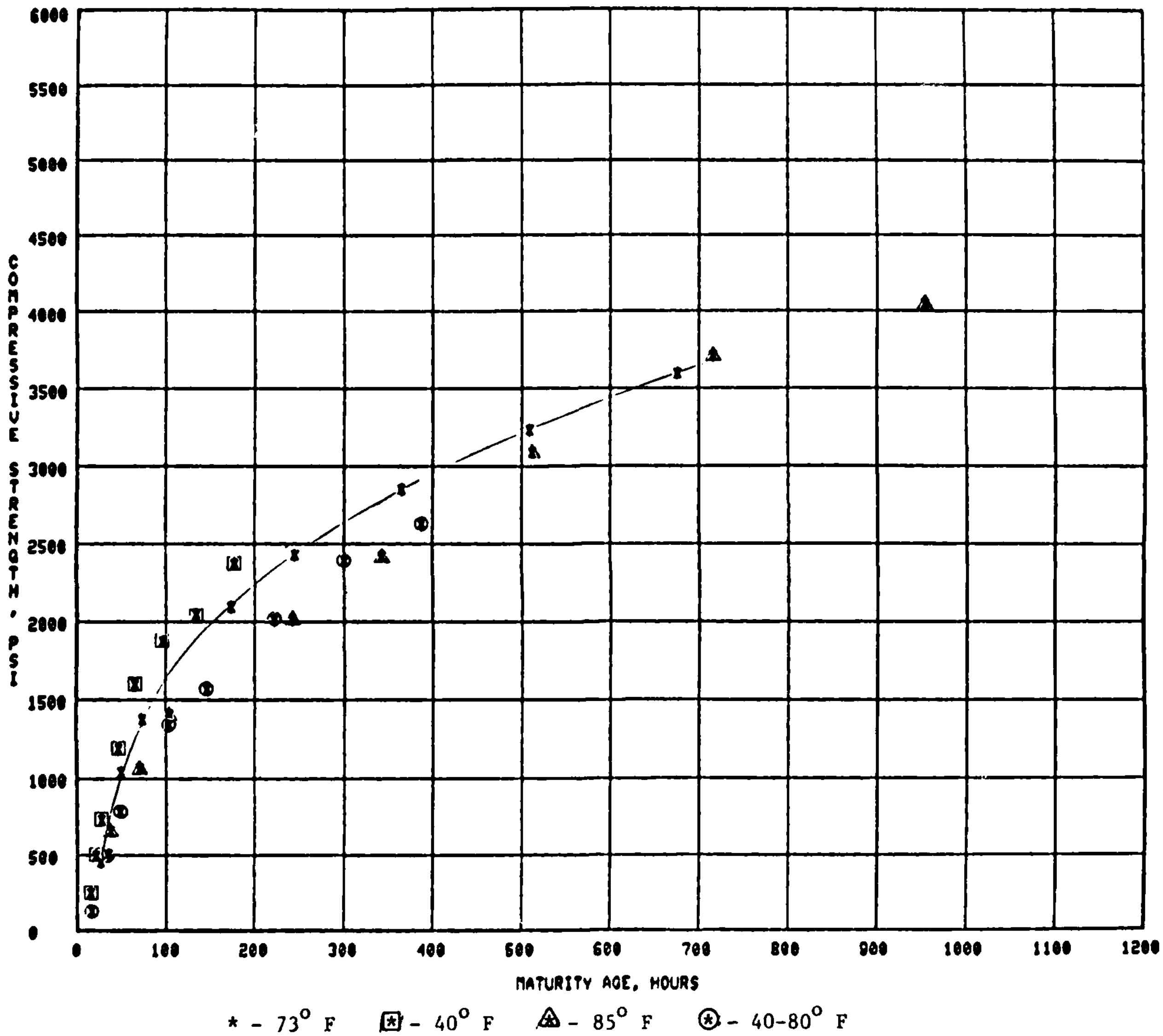
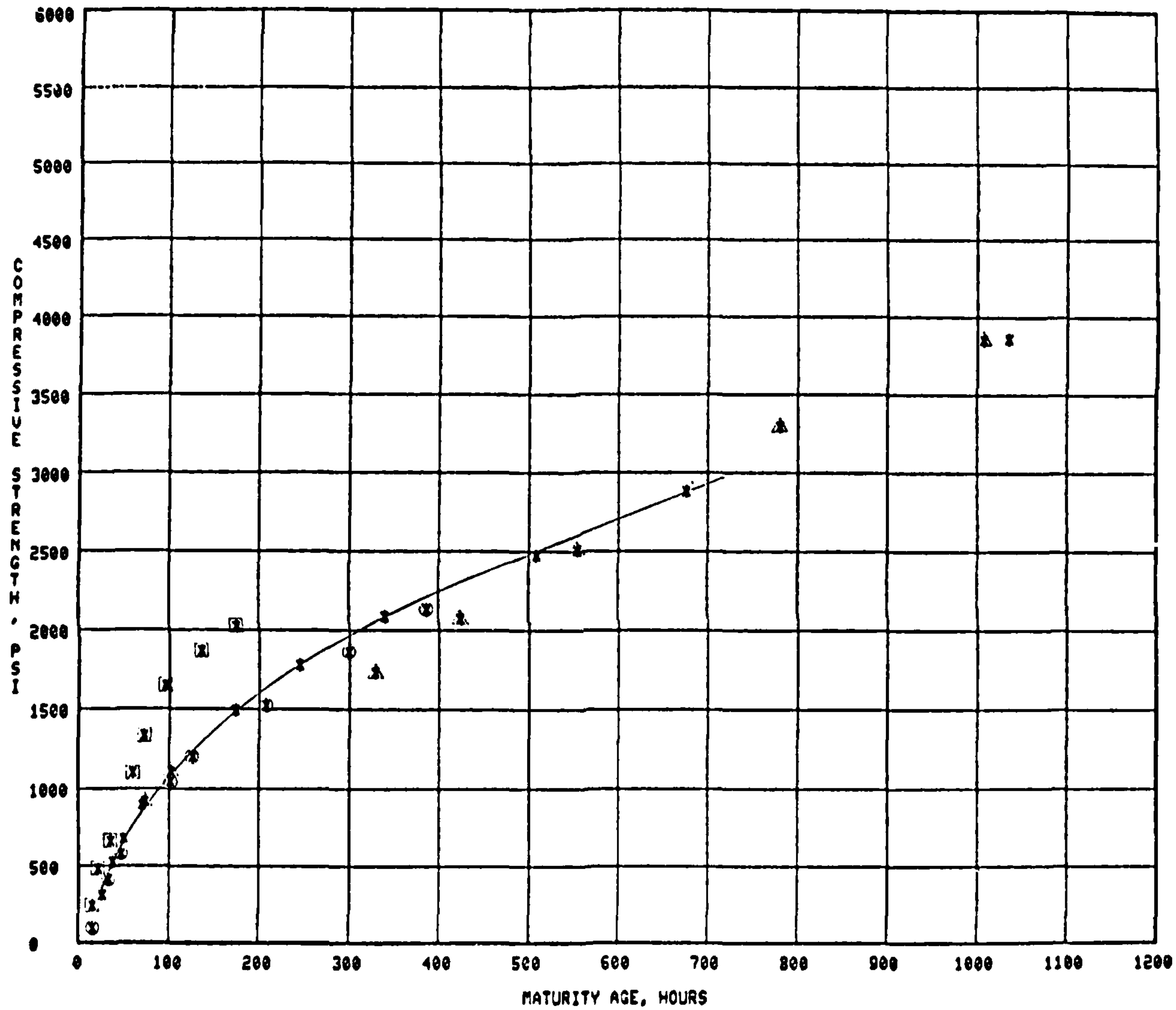


Figure 10. Relationship between compressive strength and maturity age of mortar, mixture 2



* - 73° F   [*] - 40° F   (*) - 85° F   (*) - 40-80° F

Figure 11. Relationship between compressive strength and maturity age of mortar, mixture 3

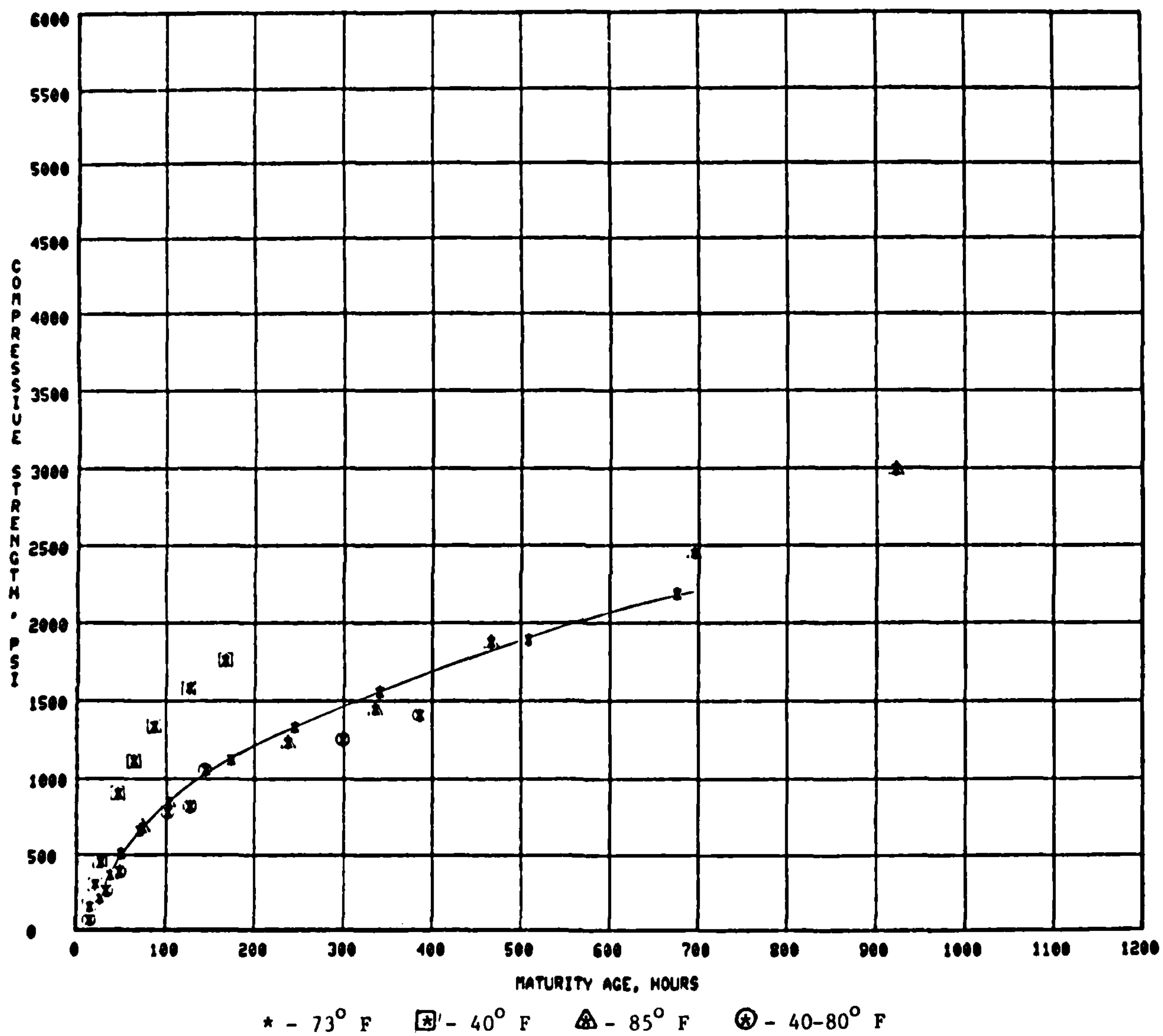


Figure 12. Relationship between compressive strength and maturity age of mortar, mixture 4

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